STUDIES OF THE CO_2 LASER

FINAL REPORT

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I. Introduction

The CO_2 laser emitting radiation in the 10.6 micron spectral region operates at higher power levels than any CW laser known to date. The first CO_2 laser was constructed by Patel, Faust and McFarlane,[1] and operated with an output power of 1 mw and an efficiency of 10^{-4}%. Patel[2,3,4] found that by using N_2 to selectively excite the ν_3 level of CO_2 in a system in which the gases are pumped through the resonant cavity, increased the efficiency by a factor of 10. Legay-Sommaire, et. al.,[5] reported an output power of 1 watt using O_2-N_2-CO_2 mixtures in a flowing system. Moeller and Rigdon[6] constructed a He-N_2-CO_2 laser capable of 15 to 20 watts output and efficiencies of the order of 5%. Patel, et. al.,[7] then reported 106 watts at an efficiency of 6% and a quasi-CW peak power of 183 watts.

The most comprehensive work on the study of the properties of the CO_2 laser was performed by the Raytheon Company and presented in a report prepared by F. Horrigan.[8] This report contains the results of studies on gain, efficiency and output power for various beam currents, coupling schemes, gas mixture ratios and total pressures of flowing CO_2 lasers, as well as fundamental studies on the electrochemistry of the laser. Also included in the above mentioned report is an excellent discussion of the optical materials that are available for use with high power infrared lasers, as well as a discussion of the quality of the optical surfaces needed for efficient lasing action, and a rather complete bibliography.

Q-switching of molecular lasers was achieved by Javan and co-workers,[9,10,11] with peak powers of about 50 k watts and pulse widths of 20 nsec or less at a pulse repetition rate of 500 Hz.

Wittemann[12] has reported a power of 103 watts at 12.5% efficiency in a nonflowing CO_2-N_2-He-H_2O mixture and suggested that the H_2O depopulates the lower level of the transition, thus increasing the output power by nearly a factor of 3.

Hetrodyne detection of CO_2 laser radiation has been performed by Brandewie, et. al.[13] This is, of course, necessary if laser communications are to become a reality.

The CO_2 laser has been used to study the intensities of the 10.6 micron CO_2 absorption bands,[14,15] vibrational lifetime[10] and relaxation,[11] fluorescence of CO_2 at 4.4 microns,[16] and thermal cracking of NH_3.[16]

As proposed, the study undertaken in the present work was to be directed toward achievement of higher power levels, efficiencies and stability through measurement of the relevant laser parameters such as beam divergence, stability, gain per unit length, line width and intensity, efficiency and farfield patterns. Since most of this work was completed by others before the funding of the grant (see references 6 through 10, and especially reference 8), it was decided to study only problems not worked with by previous investigators. The work reported here will discuss output coupling and power, stability, selective tuning, and operation of the laser in a single transverse mode.

II. Experimental Arrangements

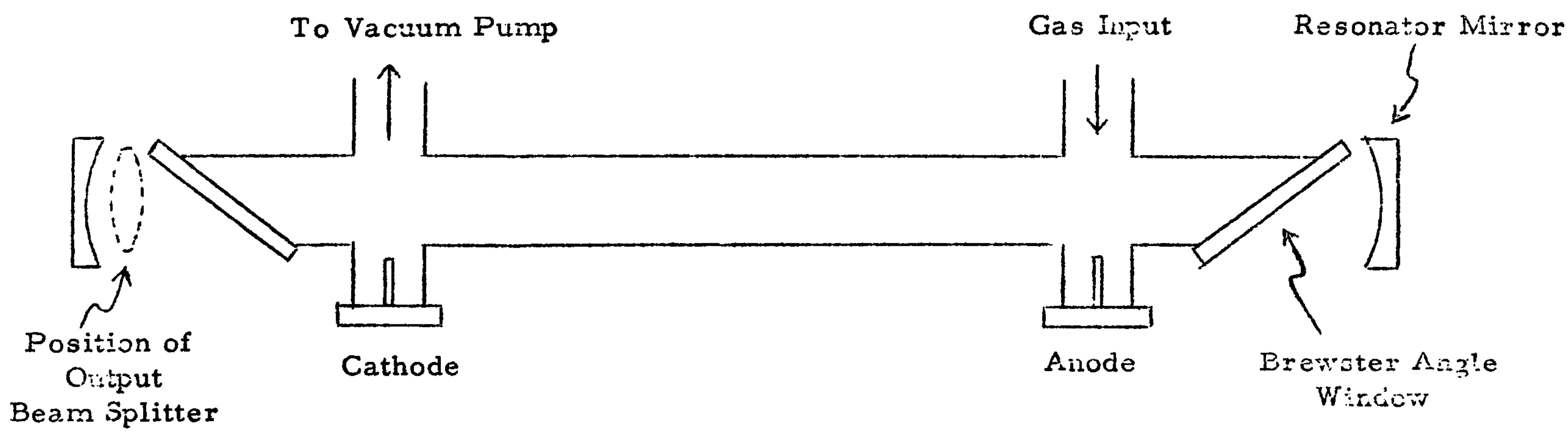
This section will be devoted to a discussion of the construction details of the lasers studied in this work and the measuring techniques used in the studies.

A. Laser Construction

The first laser constructed (henceforth called Laser I) was for operation in the flowing mode in which a gas mixture is continually leaked into and pumped from the laser plasma tube.

This laser consisted of a resonant cavity, 84 inches long with 42-inch radius spherical mirrors acting as reflectors (see figure 1). The plasma tube was assembled from one-inch I. D. glass pipe* and equipped with NaCl Brewster angle windows. The discharge was D. C. excited by a 15 KV - 50 Ma power supply. The electrodes consisted of tungsten cylinders attached to machined aluminum plates which could be easily bolted to the glass pipe flanges. The electrodes were placed about 70 inches apart in the plasma tube. CO_2, N_2 and He

* Corning Glass Works, Technical Products Division, Corning, N. Y.



The Laser Tube and Resonant Cavity

Figure 1

were separately leaked into the plasma tube through small orifices yielding a uniform gas flow. The gas flow was regulated by a valve on the vacuum pump and valves in each gas line.

Two methods of coupling power out from the cavity were used with this laser. The first consisted of coupling power through a small hole in one of the mirrors. The second consisted of reflecting the beam from a rock salt beam splitter mounted in the resonant cavity. The beam splitter method has the advantage of allowing the Q of the cavity to be varied simply by changing the angle of the beam splitter. To achieve a wide range of Q values easily, the beam splitter must be mounted in a plane perpendicular to the Brewster angle windows.

Due to the fact that vibrations from the mechanical vacuum pump used with laser I caused the laser signal to fluctuate, it was decided to construct a laser to operate in the nonflowing mode (henceforth called laser II). This laser was similar to laser I in all construction details, however, the He, N_2 and CO_2 were mixed in a small chamber where the partial pressures of the gas mixture could be monitored with a mercury manometer. The gas mixture was then transferred to the plasma tube which was sealed off. Output coupling was usually accomplished by the beam splitter technique.

It was found that the output power of this laser decayed from about 6 watts to less than 1/2 watt after about 10 minutes of operation. Since the laser tube became very warm (the temperature of the tube increased to about 100°C from room temperature) after a few minutes of operation, it was decided to construct a new laser tube with provision for cooling, to attempt to discourage the above mentioned power decay.

The third laser (henceforth called laser III) was likewise constructed from glass pipe. The resonant cavity was about 45 inches long and the active length of the discharge, about 1 meter. A stainless steel water jacket was installed over about 90% of the discharge region to prevent the excessive overheating of the laser. This water jacket was mounted on an aluminum channel filled with 600 pounds of lead for mechanical stability. The laser tube was supported by the O-rings mounted in the ends of the water jacket. No vibrations could be detected in the laser tube when the vacuum pump was running, however, this laser was normally operated in the nonflowing mode.

Power is coupled from laser III, either with a NaCl beam splitter placed in the cavity or a 20% transmitting Irtran 2 mirror.

B. Output Measurements

Copper-Constantan thermocouples with one junction connected to blackened copper receiving foils of various sizes were used for output power measurements. A Perkin-Elmer Model 13 monochromator, equipped with a 75 line/mm grating was used to study the spectra and stability of the laser output. The monochromator was used in second order where the grating efficiency is very low in order to prevent damage to the vacuum thermocouple detector. Neither of these methods of measuring the output allow us to observe fluctuations of time duration less than about 0.1 seconds.

III. Experimental Studies

A. Output Coupling and Power

As mentioned before, we have used three different methods of extracting the beam from the laser. In the first method, part of the radiation is allowed to pass through a small aperture drilled in the center of one of the cavity mirrors. This method is very inconvenient since one must determine the optimum aperture size for a particular laser by trial and error, which is, needless to say, expensive. A better way of achieving this type of coupling is to use a mirror made from an infrared transmitting material such as Irtran 2, 4 or 6, and aluminize all but a small portion in the center. Then one may easily and inexpensively vary the aperture size simply by re-coating the mirror. This method has the advantage of allowing the resonator mirrors to be placed directly on the plasma tube, eliminating the need for Brewster angle windows.

The beam splitter method described earlier was used in most of our experiments. This, of course, has the advantage that the per cent of power removed from the cavity is easily varied. Figure 2 shows the laser output power plotted as a function of the per cent of power removed from the cavity. One observes that the total output power is a slowly varying function of the amount of output coupling. This is in agreement with the results of the Raytheon group.[8] For the two power levels tested, the optimum amount of coupling is about 16 to 20%, and as much as 25% of the power could be removed without seriously reducing the total output power. We were unable to measure the power for couplings less than 15% due to the small (15°) angle of the beam splitter. The main disadvantage of the beam splitter method is that two beams are released from the laser, making it difficult to utilize the full output power.

The partially transmitting mirror method of output coupling is by far the simplest (and most expensive), however, when used in high power lasers (above 20 watts) the mirrors must be cooled due to the relatively large amounts of power absorbed from the beam by the most suitable infrared transmitting materials (Irtran 2, 4, and 6).

We have attempted to achieve diffraction coupling as discussed by La Tourette, et. al.,[17] by using a NaCl window with an aluminized circular spot about 4 mm in diameter at the center as one of the resonator mirrors. Thus far, we have not observed any laser oscillations with this arrangement. The

OUTPUT POWER
vs.
OUTPUT COUPLING

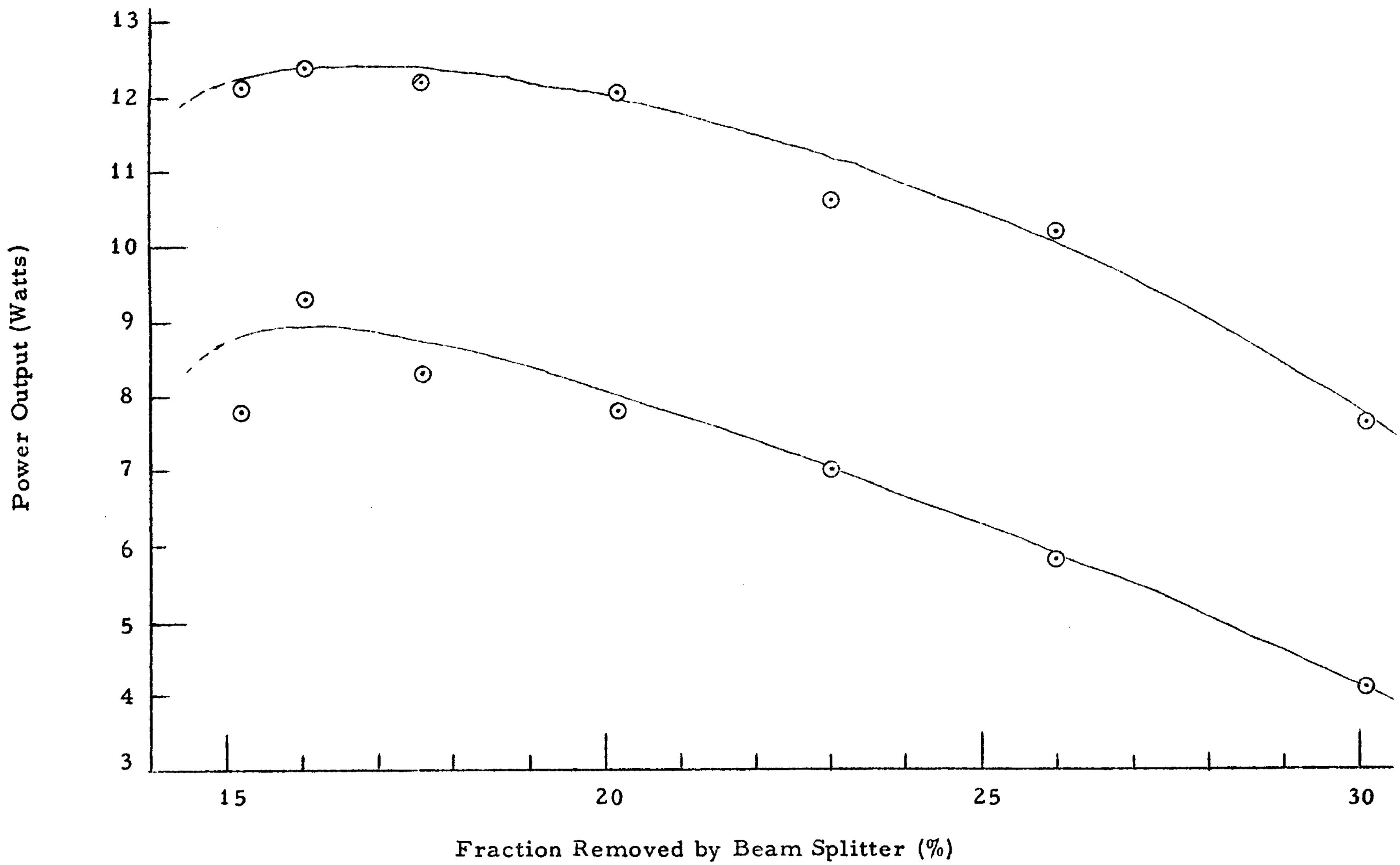


Figure 2

reason for this appears to be the poor optical surface of the NaCl window, which introduces large losses into the cavity.

Laser I, when operated with output coupling accomplished by a mirror with a 6 mm aperture at the center, produced a maximum power of 5 watts, however, when beam splitter coupling was used, the maximum output power was 18 watts. The large difference in the above output powers was due to the fact that the 6 mm aperture was too large for efficient coupling. The output power of laser I was relatively insensitive to the flow rate and mixture ratio, as long as the partial pressure of He was largest and CO_2, smallest of the three gases.

The maximum output power of laser II was only about 6 watts, even when the beam splitter output coupling was used. This low power level is explained by the low gain of the non-flowing system which prevented the laser from efficiently over-coming the large cavity losses due mainly to the Brewster angle windows. As noted before, the output power dropped from 6 watts to less than 1/2 watt after about ten minutes of operation. This was due to the overheating of the laser, electrochemical effects,[8] and release of contamination gases from the pyrex tube.[12]

When laser III was first operated, one mirror was placed inside the plasma tube, thus removing one of the Brewster angle windows from the cavity. The output power was then 10 watts using beam splitter coupling. It should be noted that although laser III is roughly one half as long as laser II, the output power was nearly twice as large. Part of this is due to the cooling, and the absence of one Brewster angle window from the cavity, and the rest probably results from the nonconfocal configuration of the resonator mirrors in laser III, allowing more of the active volume of CO_2 gas to be used. When the laser was equipped with 20 meter radius mirrors, one of which was a 20% transmitting Irtran 4 mirror, the output power was measured at 12 watts and decayed to about 6 watts in one and one-half hours. The mixture ratios for laser III were typically 1 part CO_2, 1 1/2 parts N_2 and 7 to 10 parts He. Again the output power does not strongly depend on the mixture ratio. The total pressure in the plasma tube was usually 5 to 10 mm.

B. Stability

For complete stability of the laser there must be no frequency, amplitude or spatial variations across the diameter of the beam in time. Instabilities will arise due to changes in the cavity length, electrical fluctuations in the plasma discharge, as well as variations in the flow rate and vacuum pump vibrations in a flowing type laser. Changes in the length of the cavity are the most difficult to correct and will be discussed first.

The condition for a laser cavity to act as a resonator for a wavelength λ is given by,

$$L = n\frac{\lambda}{2} = \frac{nc}{2\nu}, \tag{1}$$

where L is the length of the cavity, c is the speed of light, ν is the frequency of the radiation ($\nu = c/\lambda$) and n is an integer. The spacing in frequency between adjacent longitudinal modes is thus given by,

$$c/2L. \tag{2}$$

Now, if the length L of the cavity is changed by an amount ΔL, we see that,

$$\left|\frac{\Delta L}{L}\right| = \left|\frac{\Delta \nu}{\nu}\right|, \tag{3}$$

where $\Delta\nu$ is the change in the resonant frequency ν. If this change in length ΔL is caused by expansion or contraction of the cavity due to a temperature change ΔT, we have,

$$\Delta\nu = \alpha\,\nu\,\Delta T \tag{4}$$

where α is the coefficient of linear expansion of the material used to fix the cavity length L. It should be noted that equation (4) is independent of the length of the cavity, and that the change in temperature ΔT, required to produce a given frequency change $\Delta\nu$, is inversely proportional to ν . Thus, if a change in temperature of ΔT produces a change in frequency $\Delta \nu$ of a He - Ne laser, it will cause a change of $\Delta\nu/17$ in the frequency of a CO_2 laser. Table 1 gives the temperature variations (in degrees centigrade) required to produce a shift of 3, 30, and 60 MHz in the resonant frequency for various materials, and the associated change in cavity length ΔL .

Table 1

Temperature Changes for Various Materials
Required to Shift the Resonant Frequency by $\Delta \nu$.

$\Delta\nu$ (MHz)	Quartz	Invar	Steel	Aluminum	ΔL (microns)
3	0.25	0.1	0.01	0.004	0.2
30	2.5	1.0	0.1	0.04	2.0
60	5.0	2.0	0.2	0.08	4.0

The resonant frequency of the cavity will thus randomly wander under the optical gain curve due to small variations in the cavity temperature. The optical gain curve, if one considers only Doppler broadening, has a width at half maximum of about 60 MHz, and a gaussian shape. Thus, the temperature must be carefully controlled to insure stability.

It is well known,[18] that if a resonator cavity using spherical mirrors is not set in a confocal configuration, the various transverse modes will oscillate at slightly different frequencies. Thus, varying the cavity length would produce drastic changes in the output field patterns. We have observed this effect using

20 meter radius mirrors spaced about 1 meter apart with laser III. The patterns are easily observed on asbestos paper, and show a continuous variation from one transverse mode to another.

To study the effect of varying the cavity length, we have constructed a system to translate one of the mirrors on lasers I and II with a micrometer, thus allowing the cavity length to be changed. The output of the laser is observed with the modified Perkin-Elmer Model 13 Monochromator. In order to prevent the above mentioned changing field pattern at the entrance slit of the monochromator from producing large variations in the monochromator output due to the 10 micron slits used, the laser was operated in the lowest order transverse mode. This was accomplished by placing a mask with an aperture at the center over one of the resonator mirrors. The aperture radius r_o was approximately equal to the half intensity width of the TEM_{oon} mode given by,[19]

$$r_o = \left(\frac{LR}{\pi}\right)^{1/2}\left(\frac{2R}{L} - 1\right)^{-1/4}$$

where L is the length of the cavity, and R is the radius of the cavity mirrors. The output power of lasers I and III, when operated in the lowest order mode, was about 1 watt.

In general, five laser transitions are observed when the spectrum is scanned with the monochromator. The positions and number of lines are very reproducible from run to run, however, the relative intensities vary a few per cent. When the monochromator is positioned on the strongest line, the output is observed to fluctuate from 3 to 5%, while for weaker lines, the output fluctuates from 15 to 25%. This is easily explained by noting that for strong lines, the cavity resonance falls very near the center of the optical gain curve, while for weaker lines, the cavity is slightly off resonance. It is also observed that when the output from a strong line slowly decreases (due to a gradual variation in room temperature), the fluctuations in the output increase, while the opposite effect is observed when the power from a weak line gradually increases. The observed fluctuations correspond to cavity mode shifts, and thus output frequency shifts of 15 to 25 MHz. This is then the average frequency fluctuation in the laser output when the output is observed by a detection system with a 0.1 second response time. It should be noted that our laser cavity is fixed by aluminum supports, and thus significant gains in stability would be realized if aluminum were replaced by quartz or invar.

By moving one of the mirrors, we have found that it is quite easy to selectively suppress or enhance any of the laser transitions. It was, however, not possible to adjust the cavity length so that only one of the CO_2 lines would lase at a time. This is due to the fact that these measurements were carried out on lasers I and II for which the width of the optical gain curve (60 MHz) was about equal to the frequency spacing of the cavity modes (70 MHz). By using a cavity length of about 1 meter, the mode separation will be about 150 MHz, and it should be quite simple to suppress all but one transition.

As indicated earlier, electrical fluctuations will also lead to variations in the laser output. We have found, monitoring the laser output and the beam current, very little correlation between fluctuations in the two, indicating that within the time constants of our detecting system (about 0.1 second), there are practically no variations in the output due to electrical fluctuations.

Variations in the flow rate and vacuum pump vibrations are problems which are easily dealt with, or may be eliminated completely by using a nonflowing system, and thus will not be discussed.

We shall now discuss what we feel would be a design yielding a single mode laser operating at from 1 to 2 watts, which would have excellent stability characteristics. The laser should be a nonflowing type (mainly for convenience) and the plasma tube should be constructed from quartz similar to that described by Witteman.[12] The resonant cavity should be about 1 meter long, or less to give adequate spacing between longitudinal cavity modes to allow ease in tuning. Both mirrors should be mounted within the vacuum chamber. One mirror should be capable of being moved electrically with a peizoelectric crystal, while the other should be partially transmitting for output coupling. For greater stability, one might be able to drive one mirror with a servo system similar to the Model 119 Single Frequency, Spectra-Physics He - Ne Laser.* Either a hemispherical cavity or a two spherical reflector cavity with an aperture to spoil all but the lowest order transverse mode, could be used.

IV. Conclusions

The CO_2 laser is relatively simple to construct. The laser may be easily constructed to yield multimode output powers of 15 to 20 watts, and single mode powers of 1 watt, however, if a high degree of frequency stability is required, the construction becomes much more difficult as discussed in the last section. The output coupling may easily be accomplished by the beam splitter technique, however, we conclude that the partially transmitting mirror is much more convenient, especially if focusing the beam is required.

We have measured the average frequency fluctuation (with lifetime greater than 0.1 seconds) in the output of our lasers and find it to be 15 to 25 MHz. In conjunction with the above measurement, we have been able to selectively tune the laser simply by moving one of the mirrors.

It is felt that future work on the stability aspects of the laser should be carried out, using the hetrodyne technique,[13]

* Spectra-Physics, 1255 Terra Bella Avenue
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or using the methods described in this report and detecting the laser output with a fast infrared photoconductive detector, such as Cu:Ge.

V. Personnel

The personnel working on this problem are listed below.

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Mr. William H. Hunt
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(Mr. Hunt completed the research requirements for the Master of Science degree with his work on this project. He received the degree in June, 1967.)

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